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GIS-based Optimal Route Selection for Oil and Gas Pipelines in Uganda

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Abstract

The Ugandan government recently committed to development of a local refinery benefiting from recently discovered oil and gas reserves and increasing local demand for energy supply. The project includes a refinery in Hoima district and a 205 kilometre pipeline to a distribution terminal at Buloba, near Kampala city. This study outlines a GIS-based methodology for determining an optimal pipeline route that incorporates Multi Criteria Evaluation and Least Cost Path Analysis. The methodology allowed for an objective evaluation of different cost surfaces for weighting the constraints that determine the optimal route location. Four criteria (Environmental, Construction, Security and Hybrid) were evaluated, used to determine the optimal route and compared with the proposed costing and length specifications targets issued by the Ugandan government. All optimal route alternatives were within 12 kilometres of the target specification. The construction criteria optimal route (205.26 km) formed a baseline route for comparison with other optimal routes.

Keywords: *GIS, MCE, LCPA, Oil & Gas, pipeline routing.*

1. Introduction

Lake Albertine region in Western Uganda holds large reserves of oil and gas that were discovered in 2006. Tests have been continually carried out to establish their commercial viability and by August 2014, 6.5 billion barrels had been established in reserves [1, 2 & 3]. The Ugandan government plans to satisfy the country's oil demands through products processed at a local refinery to be built in Kabaale, Hoima district and transported to a distribution terminal in Buloba, 14 kilometres from Kampala capital city [4]. Several options have been proposed on how to transport the processed products from the refinery to the distribution terminal, this study explored one option; constructing a pipeline from Hoima to Kampala [5].

Determination of the optimal route for pipeline placement with the most cost effectiveness and least impact upon natural environment and safety has been noted by Yeo and Yee [6] as a controversial spatial problem in pipeline routing. Impacts to animal migration routes, safety of nearby settlements, security of installations and financial cost implications are all important variables considered in optimal pipeline routing. Jankowski [7] noted that pipeline routing has been conventionally carried out using coarse scale paper maps, hand delineation methods and manual overlaying of elevation layers. Although conventional, it emphasises the importance spatial data play in determining where the pipeline is installed. This has also pioneered advancement in spatial-based pipeline planning, routing and maintenance.

The approaches used in this paper are presented as an improvement and a refinement of previous studies such as those conducted by Anifowose *et al.* [8] in Niger Delta, Nigeria, Bagli *et al.* [9] in Rimini, Italy, and Baynard (10) in Venezuela oil belts. This study was the first of its kind in the study area and incorporated both theory and practice in similar settings and model scenarios for testing to support the decision making process. The study understood that evaluation of the best route is a complex multi criteria problem with conflicting objectives that need balancing. Pairwise comparison matrix and Multi Criteria Evaluation (MCE) were used to weight and evaluate different factors necessary for deriving optimal routes, and then Least Cost Path Analysis (LCPA) used to derive alternative paths that are not necessarily of shortest distance but are the most cost effective.

2. Study Area

Uganda is a land locked country located in East Africa (Fig. 1). The refinery and distribution terminal locations define the start and end points respectively for the proposed pipeline route. The refinery is located near the shores of Lake Albert at Kabaale village, Buseruka sub-country in Hoima district, on a piece of land covering an area of 29 square kilometres. This location lies close to the country's largest oil fields in the Kaiso-Tonya which is 40 kilometres by road from Hoima town. Kaiso-Tonya is also 260 kilometres by road from Kampala, Uganda's capital. The approximate coordinates of the refinery are: 1⁰30'0.00"N, 31⁰4'48.00"E. The distribution terminal is located at Buloba town centre approximately 14 kilometres by road, west of Kampala city. The coordinates of Buloba are: 0⁰19'30.00"N, 32⁰27'0.00"E. The geomorphology is characterised by a small sector of flat areas in the north-eastern region and rapid changing terrain elsewhere with elevations ranging from 574 to 4,877 metres above sea level. The most recent population census was carried out in 2014 and reported total national population results of 34.9 million covering 7.3 million households with 34.4 million inhabitants [11]. This represented a population increment of 10.7 million people from the 2002 census. Subsistence agriculture is predominantly practiced throughout the country as a major source of livelihood as well as fishing and animal grazing. Temperature ranges between 20 - 30 ºC with annual rainfall between 1,000 and 1,800 mm.

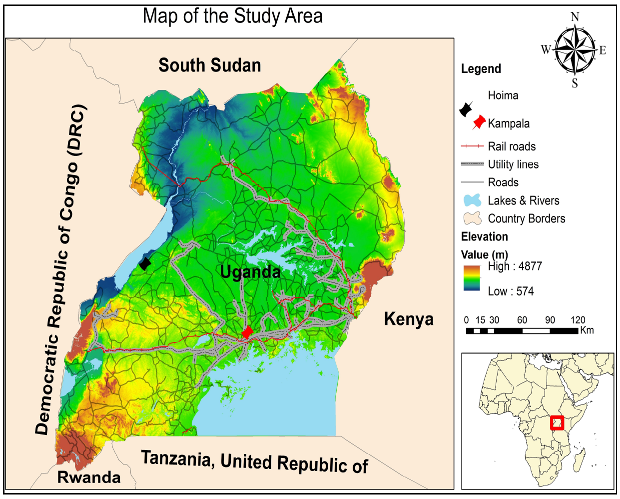

Fig. 1: Location Map of Uganda, East Africa

3. Methodology

The methodology utilised a GIS to prepare, weight, and evaluate environmental, construction and security factors used in the optimal pipeline routing. Estimates for local construction costs for specific activities such as the actual costs of ground layout of pipes, building support structures in areas requiring above ground installations, and maintenance costs were beyond the scope of the available data. However, cost estimates averaged from published values for similar projects in the USA and China [12, 13 & 14] were used to estimate the total construction costs of the optimal route. Multi Criteria Evaluation of pairwise comparisons were used to calculate and obtain the relative importance of each of the three major criteria cost surfaces and a hybrid cost surface comprising of all criteria factors. Different cost surfaces for each of the criteria were generated and evaluated to identify the combination of factors for an optimal pipeline route and the route alternatives determined using Least Cost Path Analysis.

3.1 Data

Achieving the study objectives required the use of both spatial and non-spatial data (Table 1). Data were obtained from government departments in Uganda and supplemented with other publicly available data. The choice of input factors was determined by the availability of data, their spatial dimensions and computational capacity. The study noted that there are many factors that can influence the routing of an oil and gas pipeline. However, only factors for which data were available were examined. Spatial consistency was attained by projecting all data to Universal Transverse Mercator (UTM) projection, Zone 36N for localised projection accuracy and a spatial resolution of 30 m maintained during data processing.

Table 1: Data used for designing the cost surface layers

Data type	Format	Scale	Date
Wellbores & Borehole data	Table & Points	1:60,000	2008
Rainfall & Evapotranspiration	Table & Raster	30 metre	1990-2009
Soil map	Raster	30 metre	1970
Topography	Raster	30 metre	2009
Geology	Raster	30 metre	2011
Land cover	Raster	30 metre	2010
Soil	Raster	30 metre	2008
Population	Raster & Table	30 metre	2014
Wetlands	Raster	30 metre	2010
Streams (Minor & Major)	Raster	30 metre	2007
Urban centres	Vector	1:60,000	2013
Protected sites	Vector	1:60,000	2011
Boundary, source & destination	Vector	1:60,000	2014
Linear features (Roads, Rail, Utility lines)	Vector	1:60,000	2009
Construction costs	Table	1:60,000	2009

3.2 Routing Criteria

Pipeline route planning and selection is usually a complex task involving simultaneous consideration of more than one criterion. Criteria may take the form of a factor or a constraint. A factor enhances or detracts from the suitability of a specific alternative for the activity under consideration. For instance, routing a pipeline within close distance to roads is considered more suitable compared to routing it far away from the road. In this case, distance from the road constitute a factor criterion. Constraints on the other hand serve to limit the alternatives under consideration, for instance protected sites and large water bodies are not preferred in any way for pipelines to be routed through them.

Routing a pipeline is therefore, more complex than simply laying pipes from the source refinery to the final destination. Natural and manmade barriers along possible routes have to be considered as well as the influences these barriers have on the pipeline after installation. Accurate determination of the impact of these factors and constraints on pipeline routes is usually a time-consuming task requiring a skilled and dedicated approach [15]. This study employed a criteria-based approach in order to consider the different barriers and factors required to perform optimal pipeline route selection. Datasets were selected and processed into friction surfaces and grouped into three separate strands of criteria for analysis. Fig. 2 shows the implementation methodology and the grouping of the criteria (environmental, engineering and security).

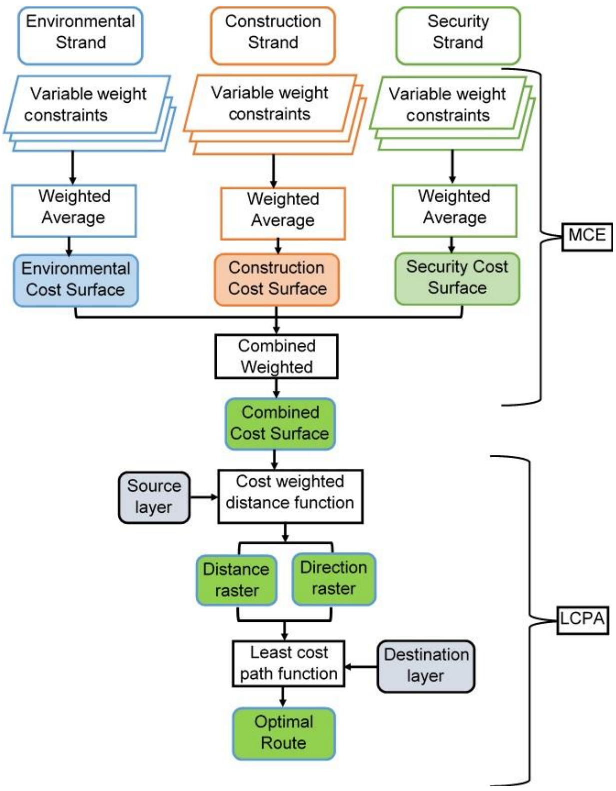

Fig. 2: Flow diagram of the implementation methodology

Environmental criteria

The environmental criteria were aimed at assessing the risks and impacts upon the environmental features found in potential corridors of the pipeline route. Two objectives were addressed, i.e. minimising the risks of ground water contamination (GWP) and maintaining least degrading effect on the environment such as the effects on land cover, land uses, habitats and sensitive areas (DEE). A GIS-based DRASTIC Model (Fig. 3) was used to assess areas of ground water vulnerability while a weighted overlay model was used in determining areas with least degrading environmental effects.

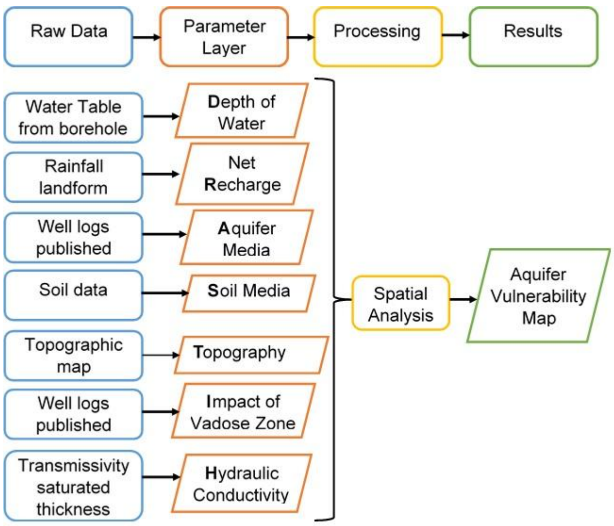

Fig. 3: DRASTIC Model

Construction criteria

Construction criteria considered factors and constraints that accounted for the costs of laying oil and gas pipelines through the route. Two objectives were addressed; maximising the use of existing rights of way around linear features such as roads and utility lines (ROW), and maintaining routing within areas of low terrain costs (HTC). Although, the criteria aimed at minimising costs as much as possible, maintenance of high levels of pipeline integrity was not compromised.

Security criteria

Oil and gas pipeline infrastructures have been vandalised and destroyed in unstable political and socio-economic environments [16]. Political changes in Uganda have often been violent, involved military takeover leading to destruction of infrastructures and resources. Therefore, the security of the proposed pipeline has always been a concern. Also, the proposed pipeline is projected to be laid above ground traversing through different land cover types, administrative boundaries and cultural groupings comprising the study area. It is therefore, imperative that security is kept at high importance in consideration of the pipeline route. Two objectives were addressed by the security criteria:

First, facilitation of quick access to the pipeline facility (QCK) and secondly, protection of existing and planned infrastructures around the pipeline route (PRT). This is in line with the observation that pipeline infrastructure poses a high security risk to the environment and communities, and is of international concern [17]. Pipeline infrastructures suffer from illegal activities involving siphoning, destruction and sabotage, disrupting the supply of oil products. Similar studies such as the Baku-Tblilsi-Ceyhan (BTC) pipeline [18] and the Niger Delta pipeline [19] reported significant effects of pipeline infrastructure vandalism and the need for proper security planning to counter such activities during pipeline route planning. It is also important that oil and gas pipelines are regularly monitored and maintained against wear and tear effects on the pipe materials, pressure, and blockages inside the pipeline. Routing in locations with ease of access for maintenance, emergency response and protection against vandalism were therefore addressed.

3.3 Weighting Criteria

The weighting criteria used were based on weights derived from literature review and expert opinions. Questionnaires were used to collate responses from experts as well as standard weights (Table 2) sourced from literature that were incorporated to weigh and derive the optimal routes.

Values were assigned to each criterion based on their degree of importance in the containing criteria. For example, gentle slopes provide solid foundations for laying pipelines so it received higher weight (lower friction value) in the construction criteria whereas steep slopes require levelling and/or support posts to raise the pipeline above ground hence it received low weight (higher friction value). Based on linguistic measures developed by Saaty [20], weights were assigned on a scale of 1 to 9 semantic differentials scoring to give relative rating of two criteria where 9 is highest and 1 is lowest. The scale of differential scoring presumes that the row criterion is of equal or greater importance than the column criterion. The reciprocal values (1/3, 1/5, 1/7, or 1/9) were used where the row criterion is less important than the column criterion. A decision matrix was then constructed using Saaty's scale and factor attributes were compared pairwise in terms of importance of each criterion to that of the next level. A summary of the normalised weights derived from expert opinion is shown in Table 10.

Table 2: DRASTIC Model Description and assigned Standard Weights

S/n	Factor	Description	Weights
1	Depth to water table	Depth from ground surface to water table.	5
2	Net Recharge	Represents the amount of water per unit area of land that penetrates the ground surface and reaches the water table.	4
3	Aquifer media	Refers to the potential area for water logging, the contaminant attenuation of the aquifer inversely relates to the amount and sorting of the fine grains	3
4	Soil media	Refers to the uppermost weathered area of the ground.	2
5	Topography	Refers to the slope of the land surface.	1
6	Impact of vadose zone	It is the ground portion between the aquifer and soil cover in which pores or joints are unsaturated.	5
7	Hydraulic conductivity	Indicates the ability of the aquifer to transmit water and thereby determining the rate of flow of contaminant material within the ground water system.	3

Source: [21]

3.4 Estimating the construction costs

The construction costs for each pipeline alternative were estimated using the economic model proposed by Massachusetts Institute of Technology (MIT), Laboratory for Energy and the Environment (LEE) (MIT-LEE) [13]. MIT applied the model to estimate the annual construction cost for a Carbon Dioxide (CO_2) pipeline. Data used were based on Natural Gas pipelines due to the relative ease of availability. The cost data were used to estimate the pipeline construction costs. Although, the rate of flow and pipeline thickness of these two types of pipelines (Natural Gas and oil) may differ, the land construction costs does not differ much. The costs of acquiring pipeline materials such as pipes, pump stations, diversions and support structures were not included in the analysis. Equation 1 illustrates the formula used to estimate the total construction cost (TCC) over the operating life of the pipeline in British Pounds Sterling (BPD):

$$TCC = LCC \times CCF + OMC \quad (1)$$

Where, LCC is the Land construction cost in BPD,
CCF is the Capital Charge Factor,
OMC is the annual operation & management costs in BPD

CCF values were defaulted to 0.15 and the OMC estimated at BPD 5,208.83 per kilometre per year irrespective of the pipeline diameter [14].
LCC were obtained from two correlation equations which assume a linear relationship between LCC and distance and length of the pipeline. Equations 2 and 3 illustrate the formula used to obtain LCC for the MIT and Carnegie Mellon University (CMU) correlation models respectively.

1. In the MIT correlation, it is assumed that the pipeline's LCC has a linear correlation with pipeline's diameter and length

$$LCC = \alpha \times D \times (L \times 0.62137) \times i \quad (2)$$

Where, α = BPD 21,913.81 (variable value specific to the user) per inch per kilometre
D is the pipeline diameter in inches
L is the least-cost pipeline route length in Kilometres
i is optional. It is the cost fluctuation index due to increase in inflation and costs in a given year. The study used the running average for year 2007 (Table 3).

Table 3: MIT Correlation Price Index

Year	Index (i)	Running Average
2000	1.51	1.47
2001	1.20	1.48
2002	1.74	1.65
2003	2.00	2.01
2004	2.30	2.20
2005	2.31	2.30
2006	2.30	2.71
2007	3.53	2.92

Source; [13]

Table 4: CMU Correlation Price Index

Year	Index (i)	Running Average
2000	1.09	1.05
2001	0.99	1.08
2002	1.17	1.16
2003	1.33	1.35
2004	1.56	1.47
2005	1.52	1.57
2006	1.68	1.59
2007	2.46	2.07

Source; [13]

2. The CMU correlation model is similar to the MIT model. However, it is more recent and departs from the linearity restriction in the MIT correlation and allows for a double-log (nonlinear) relationship between pipeline LCC and pipeline diameter and length. In addition, the CMU correlation model takes into account regional differences in pipeline construction costs by using regional dummy variables. The two correlations provided comparative results for the study area.

$$LCC = \beta \times Dx \times (L \times 0.62137)^{y} \times z \times i \quad (3)$$

Where, β = BPD 27187.55
D = pipeline diameter in inches and x = 1.035
L = pipeline length in kilometres and y = 0.853
z = regional weights = 1 (since regional weights are constant)
i is optional. It is the cost fluctuation index due to increase in inflation and costs in a given year (Table 4). The study used running average index for year 2007.

4. Results and Discussion

This section presents the results of the various analyses carried out in the study. Maps, Figures and Tables make up the content together with detailed descriptions and discussion of the results shown.

4.1 Weights used in the study

The study employed both primary and secondary data. Primary data were obtained from a sample of experts in the fields of oil and gas, environment, plus cultural and political leaders. Questionnaires were used to collect expert opinions from 20 respondents from each of the three fields. Fig. 4 shows the category of respondents and the percentage responses obtained for each of the categories. Table 10 shows the comparative responses normalised in percentage.

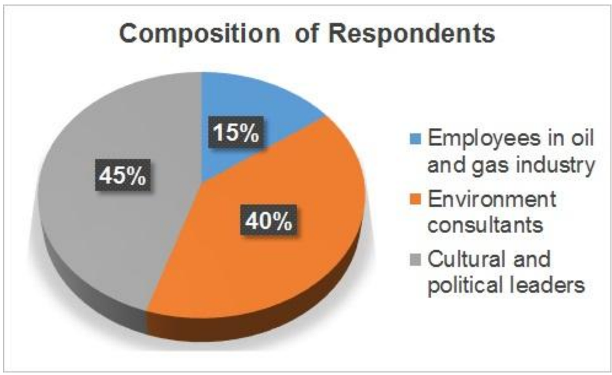

Fig. 4: Respondents collated from questionnaires

4.2 Environment cost surface

An environmental cost surface (Fig.5C) was obtained by applying equal weighting on two objective-based cost surfaces; that is maintaining least degrading effect on the environment (DEE) and protection of ground water from contamination arising from pipeline related activities (GWP), represented in Fig. 5 (A) and (B) respectively. Additionally, studies by Secunda *et al.* [22] revealed that assuming constant values for the missing layers in the DRASTIC Model produced the same results as when all seven layers were used. This study applied constant values to the three cost layers (Net Recharge, Impact of vadose and Hydraulic conductivity) based on literature because these layers have values representing a country-wide extent [23].

4.3 Construction cost surface

A Construction cost surface (Fig. 6C) was obtained by applying equal weighting on two objective-based cost surfaces; maintaining the use of areas with existing right of way (ROW, Fig. 6A) and minimising areas with high terrain cost (HTC, Fig. 6B). The cost surfaces for both ROW and HTC show that distribution of the costs cover the entire study area. Over 50% of the study area presented very low ROW with a few areas in the West, Central and Eastern parts of the study extent recording high costs indicating areas of urban concentrations, Mount Elgon to the East and protected sites covering the South-Western part of the study area and North-Eastern parts. Similarly, one protected site (licensed sites for oil drilling purposes) and all major streams (lakes and rivers) presented higher costs to the construction criteria. Much of the Central and Northern parts of the country are cheaper. Moderate construction costs are observed around areas covered by protected sites such as national parks, cultural sites, wildlife reserves and sanctuaries. This is so because the importance of these protected sites are evaluated entirely on economic terms (ROW and HTC objectives).

4.4 Security cost surface

A security cost surface was obtained from equal weighting of the QCK and PRT cost surfaces. QCK and PRT cost surfaces are the two objective-based cost surfaces for which the security criteria achieved. The results are shown in Fig. 7 (A), (B) and (C) for QCK, PRT and security criteria cost surfaces respectively. In the three maps, costs were represented as continuous surfaces.

4.5 Hybrid cost surface

The final cost surface obtained is the hybrid cost surface where the six cost surfaces (DEE, GWP, ROW, HTC, QCK and PRT) were combined and equally weighted. A continuous surface was generated as shown in Fig. 8 (A).

4.6 Optimal route

Table 5 shows the accumulated costs incurred by each route and the total distance traversed by the optimal routes. While the diameter of the actual pipes for the proposed pipeline have yet to be decided, a buffer of 1 kilometre was applied around the optimal routes to generate a strip accounting for the potential right-of-way. Also, there were no routing activities conducted for oil and gas pipeline in the study area prior to this study. The Government's estimated total distance for the pipeline route determined by a neutral criteria was 205 kilometres [4]. Therefore, this study considered the optimal route with the shortest length as a baseline route for comparisons with other optimal routes.

Table 5: Costs and lengths of the optimal routes

Optimal route alternatives	**Accumulated cost distance**	**Pipeline length (km)**	**Length difference from the proposed length**
Environmental	1,529,468.00	213.09	+8.09
Construction	1,363,801.75	205.26	+0.26
Security	1,393,417.50	209.52	+4.52
Hybrid	1,255,547.75	215.11	+10.12

The construction criteria optimal was the shortest route with a length of 205.26 kilometres, a 0.26 kilometre increase over the 205 km estimate proposed by Ugandan government. From Table 5, the environmental, security and hybrid are respectively 8.09, 4.52 and 10.12 kilometres longer than the proposed route. The baseline route also has an accumulated cost cheaper than both security and environmental criteria. However, the hybrid criteria optimal route is 1.95% cheaper than the baseline route. This suggests that the incorporation of multiple constraints and criteria in the optimal route selection minimises the resultant costs associated with routing.

4.7 The financial implications of each optimal route

Construction cost estimates from Tables 6 and 7 show that construction costs linearly vary with increases in both pipeline diameter and length across the two models. The shorter the route and the narrower the pipeline, the cheaper the construction costs. Fig. 10 shows the graphical representation of the linear relationship between pipeline construction costs and both pipeline diameter and length.

Table 6: TCC estimates for the optimal routes based on MIT Model

Optimal Routes	Pipeline length (km)	Total construction cost (MIT Model) in millions of BPD							
		Pipeline diameter in inches							
		8	16	18	24	30	36	40	42
Environmental	213.09	10.2	20.3	22.9	30.5	38.1	45.8	50.8	53.4
Construction	205.26	9.8	19.6	22.0	29.4	36.7	44.1	49.0	51.4
Security	209.52	10.0	20.0	22.5	30.0	37.5	45.0	50.0	52.5
Hybrid	215.11	10.3	20.5	23.1	30.8	38.5	46.2	51.3	53.9

Table 7: TCC estimates for the optimal routes based on CMU Model

Optimal Routes	Pipeline length (km)	Total construction cost (CMU Model) in millions of BPD							
		Pipeline diameter in inches							
		8	16	18	24	30	36	40	42
Environmental	213.09	7.0	14.4	16.3	21.9	27.6	33.4	37.2	39.2
Construction	205.26	6.8	14.0	15.8	21.3	26.8	32.3	36.1	37.9
Security	209.52	6.9	14.2	16.1	21.6	27.2	32.9	36.7	38.6
Hybrid	215.11	7.1	14.5	16.4	22.1	27.9	33.7	37.5	39.5

Considering the total construction cost for a 24-inch diameter pipeline, The total construction costs for the Government's proposed pipeline route is 29.34 million BPD, whereas for security, environmental and hybrid routes are 30.0, 30.5 and 30.8 million BPD respectively using the MIT Model. Also using the CMU Model similar trend in results are shown where the baseline route (the shortest) also doubling as the cheapest route estimated at 21.3 million BPD, followed by security, then environmental and finally hybrid at 21.6, 21.9 and 22.1 million BPD respectively.

Therefore, the financial implication of each optimal route shows the construction criteria optimal route as the cheapest and most feasible. The other three optimal routes (security, environmental and hybrid) although longer and more expensive, are all under 1.59 and 2.54 million BPD from the CMU and MIT models' construction costs estimates.

4.8 Effects of optimal routes on land cover and uses

Twelve different land cover types were considered in the study, seven of which (Table 9) were crossed by at least one of the four optimal routes. Woodland, grassland, small-scale farmland, wetlands and degraded tropical high forests all were crossed by the optimal routes. Environmental and hybrid optimal routes were the only routes that crossed Bushland. Also, construction and security optimal routes were the only routes that crossed stocked tropical high forest.

Land uses such as roads, urban centres and protected sites were crossed by at least one of the four optimal routes. Linear features (Roads, Rail roads, utility lines) and minor streams were among the most crossed features by the optimal routes. No urban and protected sites were directly crossed by the optimal routes. However, when a spatial buffer of 200m was applied around the urban centres, five urban centres and one protected site were crossed by the optimal routes (Table 8). Of the affected urban centres, four were crossed by security optimal route while hybrid optimal route crossed one urban centre. The location of the refinery is within a 1km buffer around one of the protected sites (Kaiso-Tonya Community Wildlife Management Area).

4.9 Monitoring and maintenance planning along the optimal routes

In order to properly monitor and maintain efficient operation of the pipeline, pipeline routes were preferred to be near linear features such as roads, rail roads and utility lines since they provide quick and easy access to the pipeline facility. Also, locations near streams were preferred to allow access using water navigation means. For planning purposes such as installation of monitoring and maintenance facilities such as engineering workshops and security installations, areas with clear line of sight are recommended. The study therefore performed Viewshed analysis [24] on the on topographical data to determine visible areas. Fig. 9 (B) shows the locations visible from each of the four optimal routes as determined from ArcGIS Viewshed Analysis. Although, the Viewshed analysis performed on DEM does not consider the above-ground obstructions from land cover types such as vegetation and buildings, it can be compensated by installing such monitoring facilities at the appropriate height above ground while maintaining the site location.

5. Sensitivity testing of weighting schemes

5.1 The effect of equal weighting and weights obtained from expert opinion on the optimal routes

Equal weightings were applied to combine criteria objectives and generate criteria cost surfaces as the first stage of analysis. Weights normalised from expert opinions were then used to provide comparative results of the analysis for environmental, construction and security criteria. The hybrid criteria was not affected because non-equal weightings were applied at the objectives evaluation level. The significant result was shown in the environmental criteria route where the 25% weight change in the DEE objective resulted in a 7.79% (16.61 km) increase in the overall pipeline length under environmental criteria. This was the highest change in the pipeline length followed by security criteria at (0.44 km) and lastly construction criteria at 0.05 km. Environmental criteria optimal route was also the longest route with a total length at 229.70 km followed by hybrid at 215.11 km, security at 210.18 km and lastly construction criteria at 205.31 km. Although, the environmental route had the longest length, security criteria accumulated the highest cost while construction had the least accumulated cost distances.

5.2 Application of non-equal weighting on criteria to generate hybrid route

Figures 5 & 11, shows the location of the hybrid optimal route generated from the application of equal weighting on the three criteria (environmental, construction and security). The route is within 1.51 kilometres south of Hoima town. By applying an un-equal weighting where the environmental criteria accounted for 50% of the total weight, security and construction at 25% each, the route was shifted 12 km further south of Hoima town (Fig. 11). Other urban centres such as Kitoba and Butemba that were initially close to the equal weighted hybrid route (11.83 & 11.96 kms respectively) were also shifted (50 and 20 kms respectively) away from the non-equal weighted route.

The length of the non-equal weighted hybrid route decreased from 215.11 km to 212.94 km representing a construction cost decrement of 0.3 BPD based on MIT Model for a 24-inch pipeline. Using CMU model, the construction costs decrement is at 0.2 BPD for the same pipeline diameter. Similarly, increasing the security and construction criteria by 50% respectively, while maintaining the environmental criteria weights at 25% in each case resulted in cheaper routes but presented real risk to some urban centres. For instance, the 50% security criteria weighting resulted in the hybrid optimal route crossing the buffer zone of Ntwetwe town while avoiding Bukaya by 0.2 kilometre (Fig. 9C). Although the effect of applying un-equal weighting on the hybrid criteria optimal route had no incremental effect on the total length and costs of the pipeline, the potential effects on other criteria routes are visible. However, generally un-equal weighting had minimal adverse effects upon the environmental, construction and hybrid optimal routes.

Table 8: Number of crossings by the optimal routes through buffer zones

Features	Environmental	Construction	Security	Hybrid
Roads	10	12	10	13
Lakes & Rivers	0	0	0	0
Minor Streams	14	9	13	16
Utility Lines	2	2	2	2
Rail roads	0	1	0	0
Urban centres	0	0	4	1
Protected sites	1	1	1	1
Total	**27**	**25**	**30**	**33**

Table 9: Areal coverage (square metres) of land cover type crossed by each pipeline route

Land cover	Environmental	Construction	Security	Hybrid
Grassland	2,223,000	386,100	27,900	2,014,200
Bushland	270,000	0	0	346,500
Woodland	957,600	1,208,700	600,300	560,700
Small-Scale Farmland	2,219,400	4,383,900	4,161,600	3,029,400
Wetland	27,900	261,000	288,000	76,500
Tropical high forest (stocked)	0	52,200	244,800	0
Tropical high forest (degraded)	253,800	231,300	15,300	278,100
Total	**5,951,700**	**6,523,200**	**5,337,900**	**6,305,400**

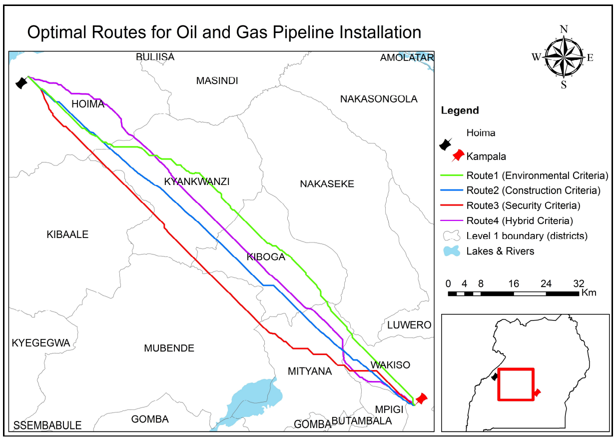

Fig. 5: Location of the optimal routes

Table 10: Summary of normalised factor weights used in determination of cost surface layers

1. DEE Objective		2. ROW Objective		3. HTC Objective		4. QCK Objective		5. PRT Objective	
Factor/ Constraint	Weight (%)	Factor/ Constraint	Weight (%)	Factor/ Constraint	Weight (%)	Factor/ Constraint	Weight (%)	Factor/ Constraint	Weight (%)
Urban centres	7.53	Linear features	5.83	Land cover	6.48	Linear features	20.16	Urban centres	20.16
Land cover	50.92	Population density	0.55	Soil	38.52	Streams	30.62	Protected sites	30.62
Protected sites	26.30	Protected sites	24.78	Topography	18.31	Dense land cover	8.13	Linear features	8.13
Wetlands	15.25	Cultural landmarks	14.38	Linear features	10.88	Urban centres	41.08	Cultural landmarks	41.08
				Geology	25.18				
Environmental Criteria		Construction Criteria				Security Criteria			

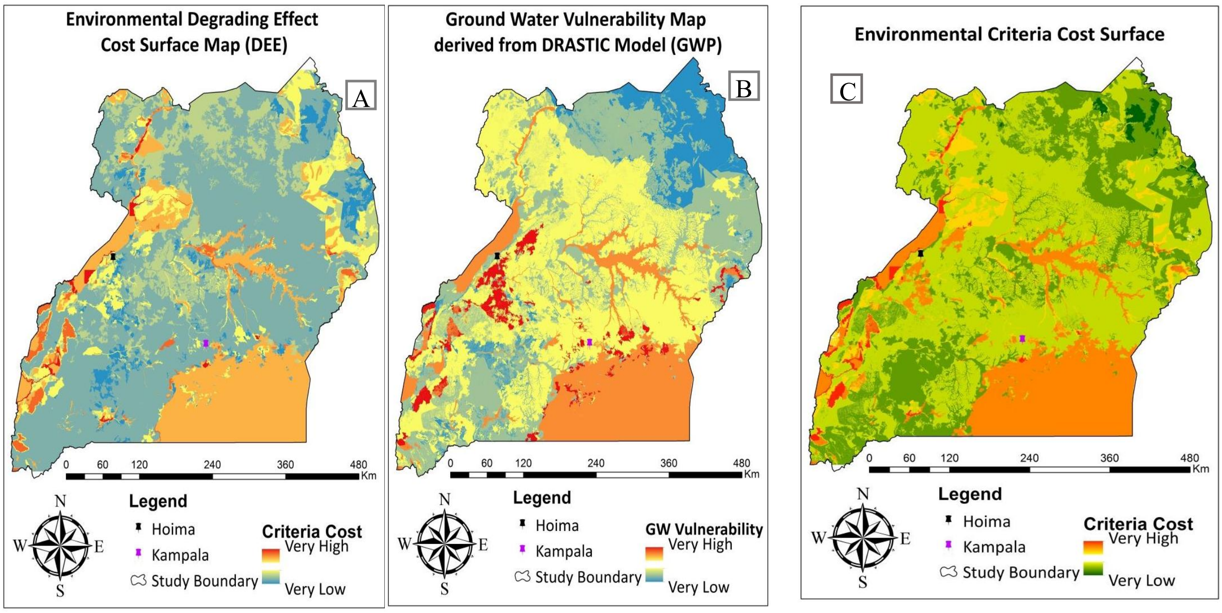

Fig. 6: Cost surface maps showing DEE (A), GWP (B) objectives and combined environmental criteria cost surface (C)

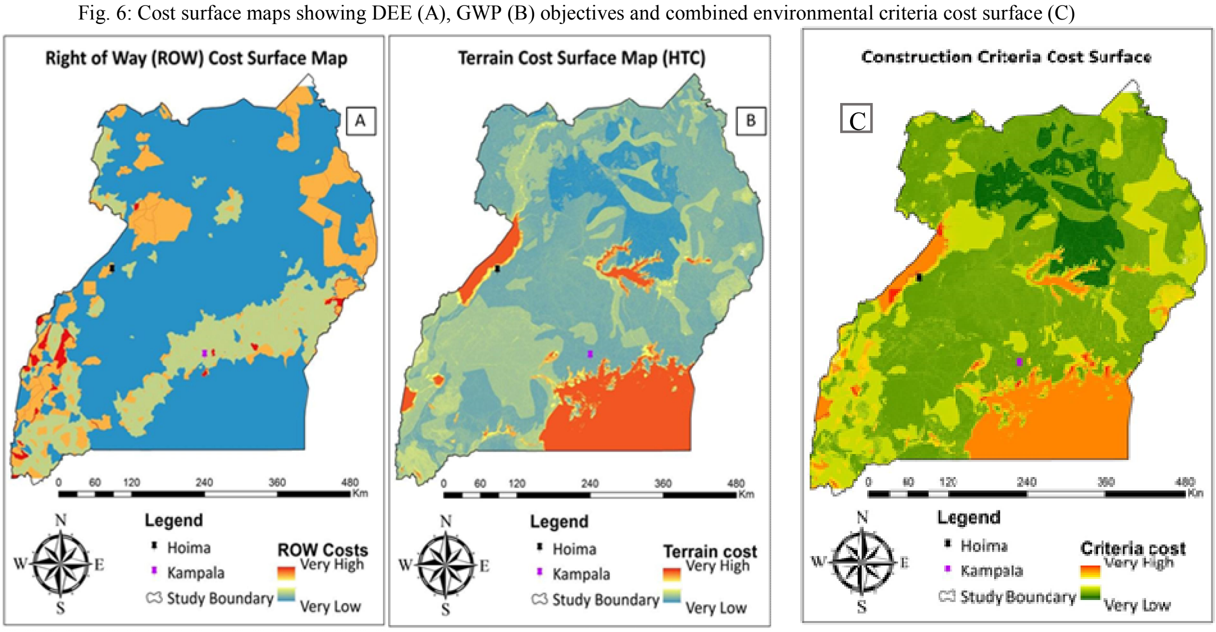

Fig. 7: Cost surface maps showing ROW (A) and HT (B) objectives and combined Construction criteria cost surface (C)

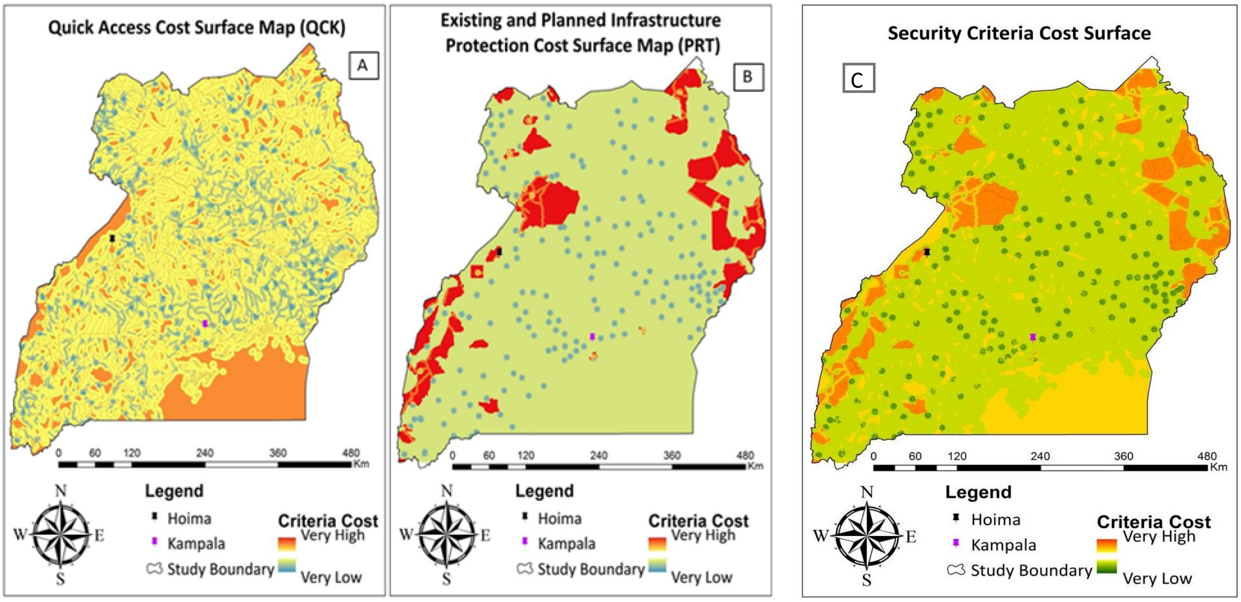

Fig. 8: Cost surface map showing the ROW objective (A) and the PRT objective (B) and combined Security criteria cost surface (C)

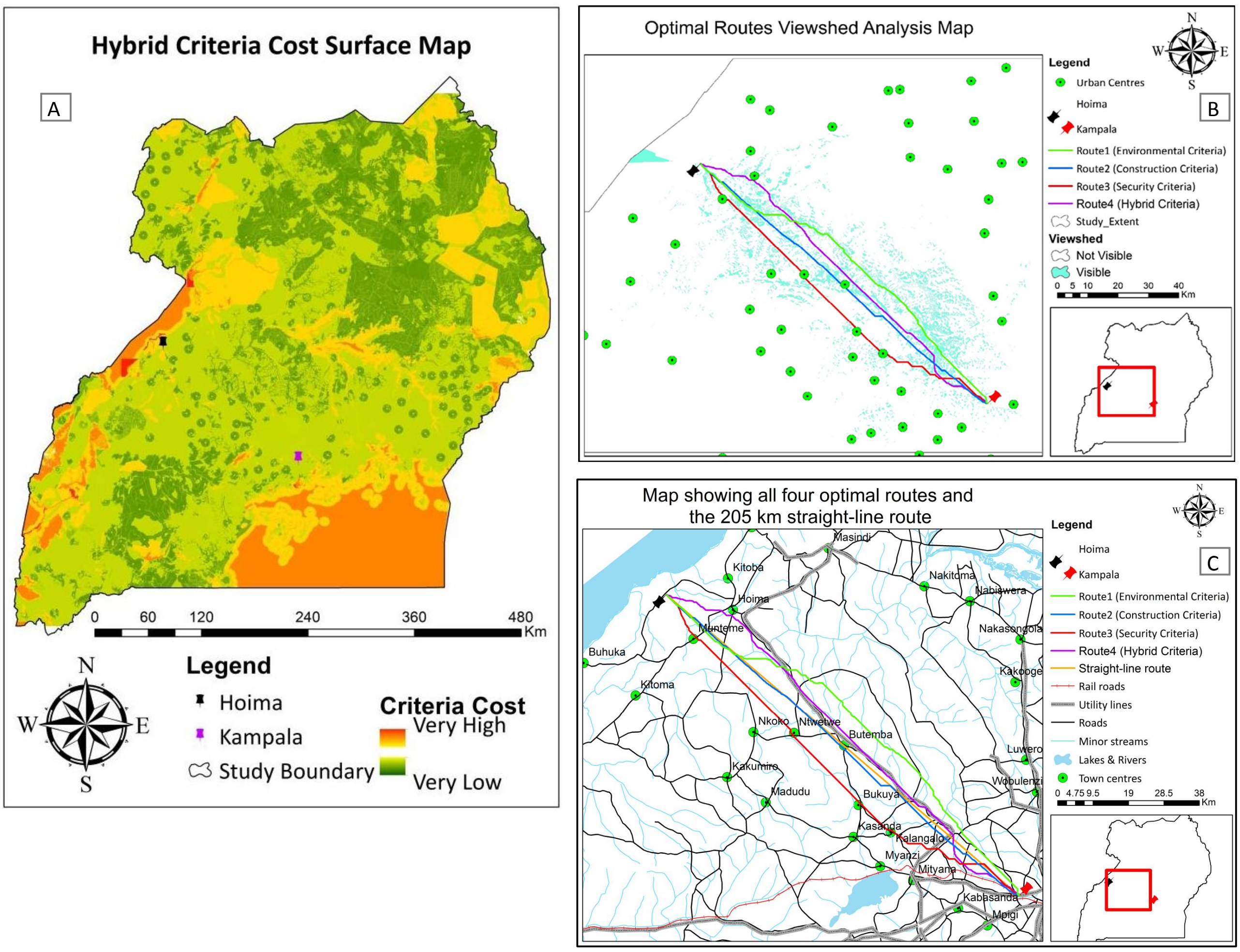

Fig. 9: Hybrid cost surface map (A), visible locations to optimal routes (B) and all five route alternatives (C)

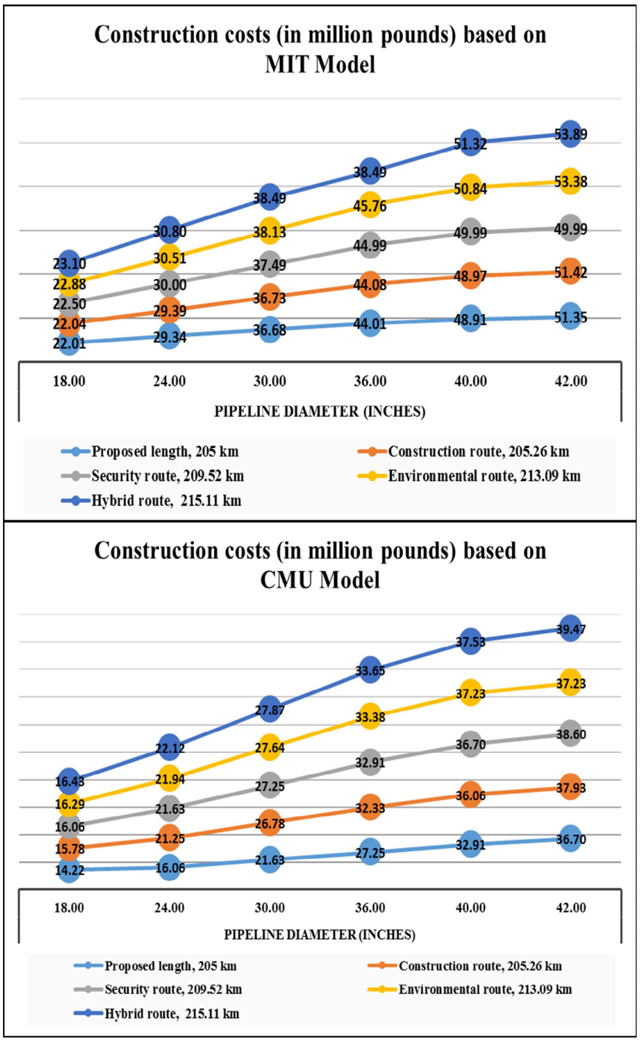

Fig. 10: Construction costs variation

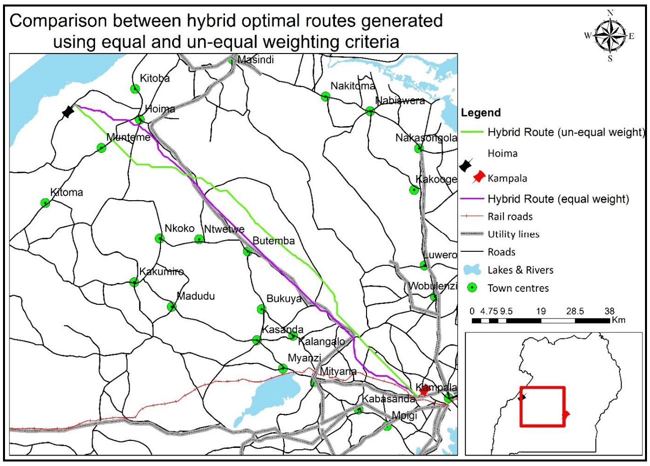

Fig. 11: Location of visible areas to the optimal routes

6. Conclusions

This paper presented a GIS-based methodology for the identification of an optimal and cost effective route for the oil and gas pipeline as well as taking into consideration the environmental, economic and security concerns associated with oil and gas pipeline routing. The effects on land cover and land uses, ground water contamination, costs of investments, human and wildlife security, and emergency responses to adverse effects such as oil spillage and pipeline leakages were considered in the routing activity. Given that governments and religious affiliations of the people can change any time, factors with long-term effects upon the installation and operation of the oil and gas pipelines were key in the decision making process. While the analyses were successful and objectives achieved, the study noted that community participation in pipeline routing is the most essential component of any complex multi criteria study. Factors such as socio-political, socio-economic and religious factors for which data are often unavailable or unreliable are recommended to be incorporated in any future studies. Similarly, land prices where compulsory land purchases are required should be conducted to estimate the pre-installation market values of land.

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References

[1] F.A.K. Kaliisa, "Uganda's petroleum resources increase to 6.5 billion barrels oil in place", Department of Petroleum, Uganda, 2014. Available at: http://www.petroleum.go.ug/news/17/Ugandas-petroleum-resources-increase-to-65-billion-barrels-oil-in-place. Last accessed: 15/06/2015

[2] C.A. Mwesigye, "Why Uganda is the Best Investment Location in Africa", State House, Uganda, 2014. Available at: http://www.statehouse.go.ug/search/node/Why%20Uganda%20is%20the%20Best%20Investment%20Location%20in%20Africa. Last accessed: 15/06/2015

[3] US EIA, "Uganda: Country Analysis Note", 2014, Available at: http://www.eia.gov/beta/international/country.cfm?iso=UGA. Last accessed: 15/04/2015.

[4] PEPD, "Uganda's Refinery Project Tender Progresses to the Negotiations Phase", Department of Petroleum, Uganda, 2014. Available at: http://www.petroleum.go.ug/news/13/Ugandas-Refinery-Project-Tender-Progresses-to-the-Negotiations-Phase. Last accessed: 15/06/2015.

[5] Business Week, "Oil boss says pipeline quickest option for Uganda", East African Business Week, 2014. Available at: http://www.busiweek.com/index1.php?Ctp=2&pI=2052&pLv=3&srI=53&spI=20. Last accessed: 05/11/2014.

[6] I. Yeo, and J. Yee, "A proposal for a site location planning model of environmentally friendly urban energy supply plants using an environment and energy geographical information system (E-GIS) database (DB) and an artificial neural network (ANN)", Applied Energy, Vol. 119, 2014, pp. 99 – 117.

[7] P. Jankowski, "Integrating geographical information systems and multiple criteria decision-making methods", International Journal of Geographical Information Systems, Vol. 9, No. 3, 1995, pp. 251-273.

[8] B. Anifowose, D.M. Lawler, V.D. Horst, and L. Chapman, "Attacks on oil transport pipelines in Nigeria: A quantitative exploration and possible explanation of observed patterns", Applied Geography, Vol. 32, No. 2, 2012, pp. 636 – 651.

[9] S. Bagli, D. Geneletti, and F. Orsi, "Routeing of power lines through least-cost path analysis and multicriteria evaluation to minimise environmental impacts", Environmental Impact Assessment Review, Vol. 31, 2011, pp. 234 – 239.

[10] C.W. Baynard, "The landscape infrastructure footprint of oil development: Venezuela's heavy oil belt", Ecological Indicators, Vol. 11, 2011, pp.789 – 810.

[11] UBOS, "National Population and Housing Census 2014, Provincial Results", 2014, Available at: http://www.ubos.org/onlinefiles/uploads/ubos/NPHC/NPHC%202014%20PROVISIONAL%20RESULTS%20REPORT.pdf. Last accessed: 13/02/2015.

[12] B. Bai, X. Li, and Y. Yuan, "A new cost estimate methodology for onshore pipeline transport of CO2 in China", Energy Procedia, Vol. 37, 2013, pp. 7633 – 7638.

[13] CCSTP, "Carbon Management GIS: CO2 Pipeline Transport Cost Estimation. Carbon Capture and Sequestration Technologies Program Massachusetts Institute of Technology", 2009, Available at: http://sequestration.mit.edu/energylab/uploads/MIT/Transport_June_2009.doc. Last accessed: 02/05/ 2015

[14] G. Heddle, H. Herzog, and M. Klett, "The Economics of CO2 Storage. MIT LFEE 2003-003 RP", 2003, Available at: http://mitei.mit.edu/system/files/2003-03-rp.pdf. Last accessed: 12/05/2014.

[15] Oil & Gas, "GIS leads to more efficient route planning", Oil & Gas Journal, Vol. 91, No. 17, 1993 pp. 81.

[16] S. Pandian, "The political economy of trans-Pakistan gas pipeline project: assessing the political and economic risks for India", Energy Policy, Vol. 33, No. 5, 2005, pp. 659–670.

[17] S.k.N. Hippu, S.K. Sanket, and R.A. Dilip, "Pipeline politics—A study of India's proposed cross border gas projects", Energy Policy, Vol. 62, 2013, pp. 145 – 156.

[18] G. Dietl, "Gas pipelines: politics and possibilities". In: I.P. Khosla, Ed. "Energy and Diplomacy", Konark Publishers, New Delhi, 2005, pp.74–90

[19] F. Onuoha, "Poverty, Pipeline Vandalisation/Explosion and Human Security: Integrating Disaster Management into Poverty Reduction in Nigeria", African Security Review, Vol. 16, No. 2, 2007, pp.94-108, DOI: 10.1080/10246029.2007.9627420.

[20] T.L. Saaty, The Analytical Hierarchy Process. New York: Wiley, 1980

[21] R.A.N. Al-Adamat, I.D.L. Foster, and S.N.J. Baban, "Groundwater vulnerability and risk mapping for the Basaltic aquifer of the Azraq basin of Jordan using GIS, Remote sensing and DRASTIC", Applied Geography, Vol. 23, 2003, pp. 303–324.

[22] S. Secunda, M.L., Collin, A.J. Melloul, "Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel's Sharon region", Journal of Environmental Management, Vol. 54, 1998, pp. 39 – 57.

[23] MWE, "WATER SUPPLY ATLAS 2010", 2012, Available at: http://www.mwe.go.ug/index.php?option=com_docman&task=cat_view&gid=12&Itemid=223. Last accessed: 15/02/2015.

[24] E.E. Jones, "Using Viewshed Analysis to Explore Settlement Choice: A Case Study of the Onondaga Iroquois", American Antiquity, Vol. 71, No. 3, 2006, pp. 523-538.

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